# NHTSA'S CRASHWORTHINESS ROLLOVER RESEARCH PROGRAM

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## ABSTRACT

In 2002, the National Highway Traffic Safety Administration (NHTSA) identified rollover crashes as one of its highest safety priorities. NHTSA formed an Integrated Project Team (IPT) specifically to examine rollover crashes and to make recommendations as to how it could most effectively improve safety in this area. This paper presents the research program undertaken to carry out the crashworthiness related aspects of these recommendations.

The crashworthiness rollover research program can be separated into two main topics, ejection mitigation and protection for non-ejected occupants. The ejection mitigation program encourages the use of occupant containment countermeasures, developing performance requirements, and test procedures for evaluating these countermeasures, and developing test procedures to evaluate rollover sensors that will be used to deploy the countermeasures. The research program for the protection of non-ejected occupants includes evaluating roof crush test methods and rollover restraint performance. NHTSA's research plans, recent results, and their significance to the overall rollover problem are presented for each of these research areas.

## INTRODUCTION

From 1995 to 2003, the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) reports an average of 261,881 light vehicles involved in rollover crashes. Rollover crashes can be especially lethal; although they comprised only two percent of crashes, they accounted for almost one-third of light vehicle occupant fatalities (including 59 percent of sport utility vehicle [SUV] fatalities) in 2003. The rate of rollover in towed light vehicles with serious occupant injury (25 percent) was nearly four times as high as for towed vehicles with no more than property damage (6 percent). Fifty-eight percent of rollover deaths in light vehicles were associated with full or partial ejections. Light-vehicle rollover crashes resulted in 10,378 fatalities in 2003 and in approximately 245,142 non-fatal injuries per year (on average) from 1995-2003.

In 2002, NHTSA identified rollover crashes as one of its highest safety priorities. The Agency formed an Integrated Project Team (IPT) specifically to examine rollover crashes and make recommendations as to how it could most effectively improve safety in this area. The IPT report, "Initiatives to Address the Mitigation of Vehicle Rollover", was published in the Federal Register in June 2003 (68 FR 36534) [1]. It included vehicle strategies covering both the crash avoidance and crashworthiness perspectives. This report made wide-ranging recommendations on ways to mitigate rollover crash injuries, including several vehicle strategies, behavioral strategies, and roadway strategies. This paper documents the ongoing crashworthiness research efforts that were recommended by the IPT report.

Due to the complex nature of rollover, NHTSA has recognized the need to take a comprehensive approach to developing potential solutions. The Agency's crashworthiness efforts to reduce rollover fatalities and injuries focus reduction of occupant side window ejection, improvement to roof crush protection, and rollover restraint system effectiveness.

## EJECTION MITIGATION

Ejection is a major cause of death and injury in light-vehicle rollover crashes. There were 9,859 people killed in 2003 and approximately 44,223 had non-fatal injuries in tow away crashes each year (on average) from 1995-2003 when they were ejected from light vehicles. Two-thirds of these ejections occurred in crashes involving rollover. Occupants stand a much better chance of surviving a crash if they are not ejected from their vehicles. For each year from 1995 to 2003, approximately 5,885 people were killed and 5,451 seriously injured when they were ejected through side windows.

Among the promising technological innovations to prevent occupant ejections are the use of side curtain air bags and improved glazing. NHTSA submitted a report to Congress on ejection mitigation using advanced glazing materials in November 2001. In May of 2004, NHTSA issued a Notice of Proposed Rulemaking (NPRM) proposing to upgrade Federal Motor Vehicle Safety Standard Number (FMVSS No.) 214 "Side impact protection" which, among other things, proposed to require a side impact pole test that would provide improved head protection to occupants. This proposed regulation would likely result in the fleet-wide installation of side air bags to protect the head. While these air bags would not necessarily be designed for occupant containment or for deployment in rollovers, they would prevent some number of side window ejections. This is the first phase of a three-phase approach the agency is taking to reduce side window ejections. The second phase is to establish occupant containment performance requirements, and develop test for this purpose. Details of the Phase 2 research are presented below. The third phase is to establish performance requirements for rollover sensors, to ensure that the air bags will deploy in a rollover crash. The agency has not conducted specific research in this area yet, but has collected considerable information in its effort to develop a research plan for rollover sensor performance requirements.

### Phase 2 Objectives

The first objective for the Phase 2 research is to develop a test methodology, including a test device, to evaluate the retention performance of potential ejection mitigation systems. This includes establishing practical test parameters such as impact speed, impact locations, and performance criteria. For a test to be acceptable, it must show that good (or poor) performance in the laboratory test correlates to good (or poor) performance in the real world. The second objective is to evaluate the test methodology and performance criteria on potential ejection mitigation systems.

### Test Methodology

**Guided Impactor** - NHTSA has been conducting research on ejection mitigation for several years. Since full-vehicle rollover crash tests have substantial variability in vehicle and occupant kinematics [2], it is necessary to develop a component-level test to evaluate the performance of potential ejection mitigation systems. Previous research with advanced side glazings has shown that guided impact testing is an acceptable method for measuring excursion. NHTSA's advanced side glazing status report [3] details the development of an impactor designed to replicate the loading of an occupant's head and shoulder during typical ejection situations. In brief, it consists of an 18 kilogram mass guided through a bearing attached to two supporting rails (see Figure 1). An existing featureless free-motion headform was selected for the impactor face. This rigid headform, covered with a headskin, was originally designed for the upper interior head protection research program. It averages the dimensional and inertial characteristics of the frontal and lateral regions of the head into a single headform [4]. Since it is a guided impactor, only uni-axial motion is measured, and it is capable of measuring dynamic deflection during an impact. The propulsion unit is based on a device by the General Motors Corporations [5], scaled to accommodate the heavier mass. The impactor can be placed inside the vehicle for testing the side window areas, and it can be positioned to strike different locations in those areas.

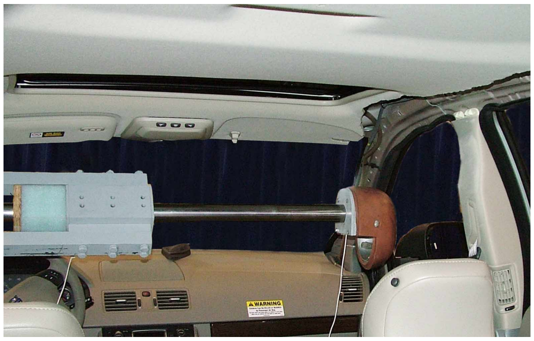


**Figure 1. 18 Kg guided impactor.**

**<u>Test Parameters</u>** - The level of a countermeasure's performance measured by the guided impactor can vary depending on impact locations and speeds used. A test matrix was proposed in a previous paper outlining the status of NHTSA's Ejection Mitigation Research to date [6]. An expanded matrix was used in subsequent testing. Each of the impact locations were evaluated using the test matrix shown in Table 1. The primary goal of this test matrix was to determine if the guided impactor is a suitable device for measuring the occupant retention performance of a variety of possible countermeasures, and if it is, to help identify and establish practical performance criteria.

**Table 1.**
**Guided Impactor Test Matrix.**

| Impact Speeds | 16 kph | 20 kph | 24 kph |
|---|---|---|---|
| Delay Time | 6 sec | 1.5 sec | 1.5 sec |
| Advanced Glazing Systems Only | | | |
| Inflatable Systems Only | | | |
| Inflatable Systems With Glazing (pre-broken) | | | |
| Inflatable Systems With Glazing (unbroken) | | | |

Different sized occupants traveling on various trajectories may encounter an opening at numerous locations within the side window portal. Therefore, four impact locations were identified to evaluate a countermeasure's window coverage and retention capability, as shown in Figure 2.

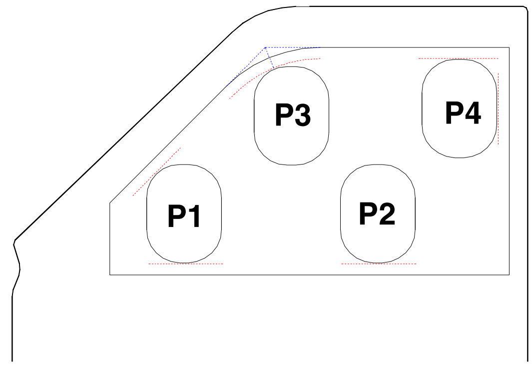


**Figure 2. Headform impact locations.**

Positions 1 and 4 are located at the extreme corners of the window/door frame and positioned such that a 25-millimeter gap exists between the outermost perimeter of the headform and window frame as represented by the dashed lines in Figure 2. Position 3 is near the transition between the upper window frame edge and A-pillar (diagonal) edge. Previous research with advanced side glazings identified this area as a weak point in limiting excursion. It is located by bisecting the angle that is created at the intersection of two lines running parallel to the upper and diagonal window frame edges. A 25-millimeter gap is maintained between a point on the outermost perimeter of the headform and the bisection point on the window frame edge. Position 2 is located at the longitudinal midpoint between positions 3 and 4, and positioned such that the lowest edge of the headform is 25 millimeters above the surface of the door at the bottom of the window opening.

At each impact location, different impact speeds and different time delays between air bag deployment and impact were used. Rollovers can be relatively long events. The reason for the time delays is that inflatable ejection countermeasures tend to lose pressure after deployment. This pressure can affect the retention capability of the countermeasure. To simulate ejection late in a rollover event, the air bags were impacted at an impact speed of 16 kilometers per hour after a delay of six seconds. To simulate an ejection early in a rollover event and in a side impact, a delay time of 1 ½ seconds was used. This condition was evaluated at two speeds, 20 and 24 kilometers per hour. The impact speeds were selected upon the film and data analysis reported in reference 3.

**Ejection Countermeasure Candidates** - Three ejection countermeasures were examined: two experimental roof rail mounted inflatable systems and advanced side glazings developed under previous NHTSA research. Details of the countermeasures used in testing can be found in reference 6, with one exception. The inflatable device known as the Advanced Head Protection System (AHPS®) developed by Zodiac Automotive US (formerly Simula Automotive Safety Devices, Inc.) was furnished with a modified design that allowed the device to deploy closer to the bottom of the window opening, thus providing more window coverage than the previous design (see Figure 3). The other inflatable system tested, a prototype window curtain provided by TRW, is shown in Figure 4.

**Figure 3. Modified advanced head protection system (Zodiac).**

**Figure 4. Prototype window curtain (TRW).**

Both inflatable systems were evaluated for their effectiveness as stand-alone devices. In addition, the inflatable device supplied by TRW was tested for its effectiveness as part of a combination system (air bag plus side glazing). For testing described in this paper, only advanced glazing systems in the laminated construction were used and door/window frame modifications were limited to the C-channel along the vertical sides (A and B-pillar).

**Guided Impactor Test Results**

The two air bag designs were placed on a Chevrolet C/K pickup cab and used to evaluate the test methodologies described previously. Each curtain design was evaluated for allowable excursion (impactor displacement) beyond the side window plane. This zero reference point was established by touching the impactor face to a piece of standard tempered glass prior to testing. Negative numbers indicate that the impactor face did not reach the zero plane reference. The air bags were pre-inflated with shop air to pressures previously measured in deployments with an inflator (see Table 2).

**Table 2.**
**Air Bag Static Pressures.**

| | 1.5 sec | 6 sec |
|---|---|---|
| TRW Air Curtain | 62-kPa | 28-kPa |
| Zodiac modified AHPS® | 79-kPa | 49-kPa |

Results for guided impactor tests on TRW's prototype window curtain are shown in Figures 5 through 7. Impact position 1 was not sufficiently covered by this air bag and was unable to stop the impactor before the limits of travel were reached (about 180 millimeters beyond the plane of the vehicle window for this test setup). When combined with advanced laminated glazing, excursion was limited at the 16 and 20 kilometers per hour impacts, with the unbroken laminate showing some improvement over the pre-broken glazing.

At position 2, the window curtain stopped the impactor before reaching its physical stops at the three impact speeds. Excursion measurements were greatly improved with the addition of both unbroken and pre-broken laminated glazing.

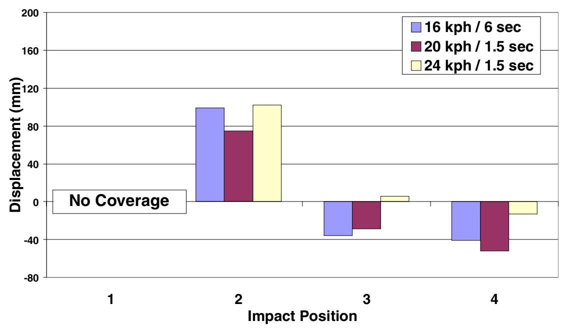


**Figure 5. Maximum excursion beyond window plane - TRW air curtain system.**

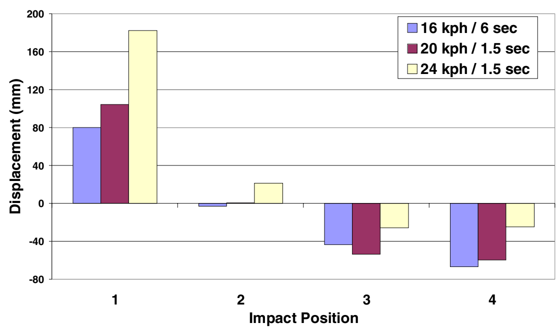


**Figure 6. Maximum excursion beyond window plane – TRW air curtain/pre–broken laminated glazing.**

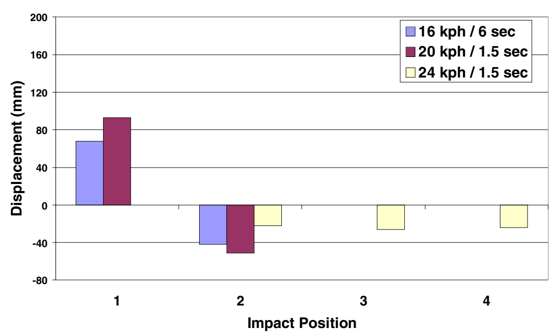


**Figure 7. Maximum excursion beyond window plane – TRW air curtain/unbroken laminated glazing.**

At positions 3 and 4, this inflatable system was able to contain the impactor at the three impact speeds with little or no excursion beyond the plane of the window. The addition of un-broken or pre-broken glazing produced only slightly better results, suggesting that the air curtain was predominantly responsible for limiting excursion at these impact locations.

Results for partial testing with Zodiac's modified Advanced Head Protection System are shown in Figure 8. Testing was restricted to positions 1 and 2 due to limited availability of this inflatable system. In the 16 kilometer per hour tests, with the lower bag pressure, the headform did not go beyond the plane of the window, while the headform was contained inside the vehicle at 20 kilometers per hour, with the higher bag pressure. Finally, at the 24 kilometers per hour impact condition, 12 and 19 millimeters of excursion were produced at positions 1 and 2, respectively.

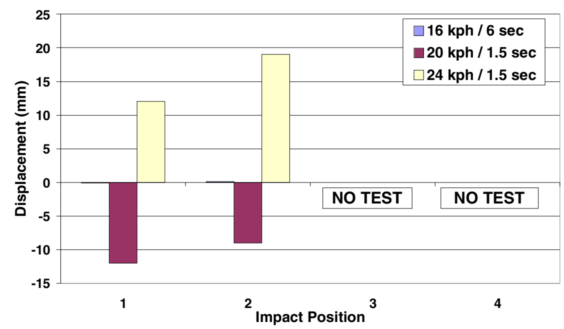


**Figure 8. Maximum excursion beyond window plane – Zodiac modified AHPS®.**

__Repeatability__ - Several impact conditions were chosen for a study of the repeatability of the test parameters. The results are shown in Figure 9. Overall, the repeatability was quite good, although the 24-kilometer per hour tests at position 2 had the most variability (102 and 82 millimeters). A third test was conducted at position 2 under these same conditions (not shown in Figure 9), and it also resulted in 82 millimeters of excursion. One possible reason for the variability is that there was more tearing in the bag material at one of the side rail attachment points in the first test than in the next two tests. It is not known how much this tear affected the headform excursion.

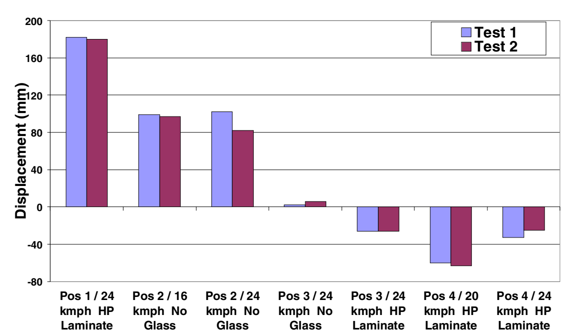


**Figure 9. Repeatability results for selected impact conditions.**

**Dynamic Rollover Fixture**

A series of tests was conducted on the Dynamic Rollover Fixture (DRF) using an unrestrained Hybrid III 6-year old dummy to further determine the effectiveness of experimental roof rail mounted inflatable devices, advanced side glazing, and combinations of these systems in retaining occupants during rollover type crashes. The testing also evaluated the countermeasures' potential for head and neck injury. These DRF tests build on the test matrix that was presented in reference 5. In previous testing with 50th percentile male and 5th percentile female Hybrid III dummies, loading on the inflatable devices in some tests produced gaps between the devices and the top of the door, allowing the shoulder and arm to escape below the bags. The current tests were conducted to determine if the gap produced was substantial enough to allow a smaller stature occupant to pass through.

**Baseline Testing** - Baseline testing was conducted with an open side window to determine if the DRF could produce full body ejections for the 6-year old dummy as it had done with the 50th percentile male and 5th percentile female dummies. The general kinematics for the 6-year old were similar to the other dummies, and full ejection was achieved in this testing configuration.

**Inflatable Device Testing** - In the testing of inflatable devices reported in this paper, the air bags were pre-deployed, and their set pressure was maintained throughout the test by the use of an air reservoir tank mounted on the platform. A small series of tests was conducted with the 6-year old dummy in upright-seated positions (no booster seat). Both inflatable devices contained the torso, head, and neck of the dummy, so complete ejection did not occur. However, the dummy loading on the systems produced gaps that did allow an arm and/or hand to pass through in some tests. The gap with the TRW system was similar to that seen in previous testing. The gap produced in testing with the modified AHPS was significantly less than in previous testing due to the modified design.

Another small series of tests was conducted with the 6-year old dummy lying in the prone position to simulate a near worst-case ejection condition. Using a specially constructed bench, the dummy was placed on its back at the height of the bottom of the window opening. The dummy was positioned on the table such that initial contact with the inflatable systems occurred at both positions 1 and 2 of the guided impactor test setup.

The dummy was completely ejected at both positions 1 and 2 in testing with the TRW prototype window curtain, while the modified AHPS contained the dummy inside the test buck in all testing. Figure 10 shows the prone 6-year old dummy being ejected under the TRW bag at position 1. Adding pre-broken advanced laminated glazing with the TRW system produced better results. The combined system contained the dummy inside the test buck in all tests conducted with this configuration.

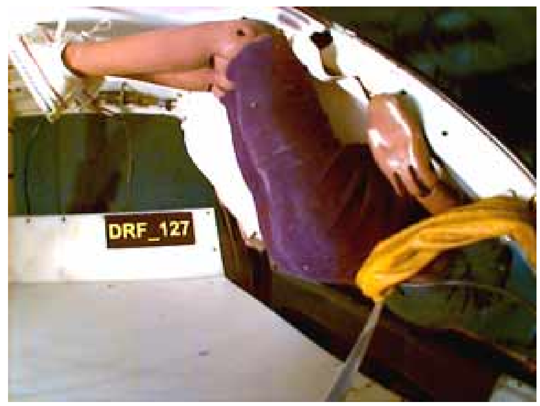


**Figure 10. 6-year old dummy ejection.**

**PROTECTION FOR NON-EJECTED OCCUPANTS**

FMVSS No. 216 "Roof crush resistance" establishes strength requirements/intrusion limits for passenger car and light truck roofs for protection in rollover crashes. Based on NHTSA's analysis of the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) 1997-2002) data, approximately 1,400 belted, non-ejected occupants receive a serious or fatal maximum AIS injury to the head/neck/face each year when roof intrusion is present over the occupants' seating position. NHTSA has conducted vehicle tests to evaluate current fleet performance and potential new test procedures to upgrade FMVSS No. 216.

Belt slack and belt stretch inherent to some current lap/shoulder safety belt systems may fail to sufficiently restrain occupants from contacting the undeformed roof during a rollover crash. Thus, in order to realize significant benefit from increased roof strength, improved performance of restraints in rollovers may also be necessary. NHTSA will research the restraint performance and benefits or dis-benefits of systems such as pretensioners, belt load limiters, integrated belts and other advanced belt systems that may be activated with a rollover sensor.

**ROOF CRUSH RESEARCH**

The current FMVSS No. 216 requires that a passenger car roof withstand a load of 1.5 times the vehicle's unloaded weight or 22,240 Newtons (5,000 pounds), whichever is less, to either side of the forward edge of the vehicle's roof, with no more than 127 millimeters (5 inches) of crush. The same standard applies to light trucks and vans with a GVWR of 2,722 kilograms or less (6,000 pounds), without the 22,240 Newton force limit. The FMVSS No. 216 test procedure applies a quasi-static load to the roof through a load plate. This plate is placed over the driver or right front passenger seating position and is pitched forward 5 degrees and rolled 25 degrees, outside edge down, relative to the vehicle.

In the 1980s and 1990s, NHTSA conducted research toward a possible upgrade to FMVSS No. 216. This included conducting full-scale rollover crash tests, and one finding from this work was that this type of test was not repeatable. Additional research was performed, including a hardcopy analysis of real-world rollover crashes, extended quasi-static testing (i.e. crushed beyond current requirement), and inverted vehicle drop testing [7,8,9]. There were two significant findings from these efforts. First, the typical roof structure failure modes were the same for all three types of laboratory tests and were similar to those observed in the real-world rollovers. Second, while the peak loads from the dynamic drop tests were higher than those from the quasi-static tests, a correlation was found between the energy characteristics of the two types of tests. Additional drop and quasi-static tests were performed on one vehicle model in an attempt to validate this correlation. This effort produced more error than was desired, so the relationship was not validated.

During this time, several attempts were made to find a relationship between the level of roof crush and the injuries that occur in rollover crashes. Rollovers have complex and widely variable kinematics. When an occupant receives a significant injury from contact with roof structures, it is generally not clear if the occupant moved out of the seat to contact the roof, or if the roof contacted the occupant. Further complicating this effort was the lack of a measure of crash severity, which prevented researchers from separating vehicles damaged by a severe crash environment from vehicles with a weak roof structure. There have been several attempts to use quarter turns as a surrogate for rollover severity, but these have only been partially successful [10]. These older attempts to relate roof deformation and occupant head injury were generally not successful,. One study identified a relationship between injury and the amount of interior headroom reduction [11].

This paper is intended to provide a summary of the NHTSA roof crush research program. More detailed descriptions of the testing and discussion of the results are contained in the reports of references 12 and 13.

**Objectives** -There were three major objectives for this research. The first was to evaluate whether load plate angles that produced more lateral loading resulted in more realistic roof crush patterns. The second was to obtain roof force-displacement characteristics from a sampling of recent model vehicles. The third was to evaluate methodologies for relating roof strength to headroom.

**Approach** - This research was divided into three phases. The first objective was addressed in Phase 1, while the second objective was addressed in Phases 2 and 3. Methodologies for relating roof strength to headroom parameters were evaluated in all three phases, with one method used in Phases 1 and 2, and a second method used in Phase 3.

Based on previous NHTSA research, it was decided that the quasi-static roof crush procedure would be used in this program. The hardware and test parameters specified in the current FMVSS No. 216 were used, except that the tests were conducted until 254 millimeters (10 inches) of exterior crush was achieved, rather than the 127-millimeter maximum specified in the standard. This was to obtain roof force-displacement characteristics at a crush level well beyond that required in the current standard. Also, alternative load plate angles were used in Phase 1, and non-standard equipment and procedures were used in all three phases to obtain the headroom information.

**<u>Phase 1 Summary</u> -** To evaluate the effect of load plate angle, finite element (FE) roof crush simulations were performed on two vehicle models – 1997 Dodge Grand Caravan and 1998 Chevrolet S-10 pickup. Based on the results of these simulations, two sets of load plate angles were selected for use in the test program. These were the standard FMVSS 216 angles of five degrees pitch, 25 degrees roll (5x25 degrees) and an alternative set of ten degrees pitch, 45 degrees roll (10x45 degrees).

Roof crush tests were then performed on these two vehicle models, as well as on a pair of 2002 Ford Explorers. Each model was tested using the two sets of load plate angles (six total tests). The results of these tests were evaluated to determine whether any trends were observed when comparing the force-displacement data obtained from the 5x25 degree and 10x45 degree load plate angle configurations, and whether one configuration resulted in more realistic roof crush patterns than the other.

There was no trend observed in the force-displacement curves and peak loads between the two plate angle configurations. The S-10 pickups and Explorers exhibited similar characteristics, and the 10x45 degree configuration produced the higher loads. In contrast for the Caravans, the force-displacement traces were generally similar, and a slightly higher load was produced with the 5x25 degree plate angle configuration. Similarly, there was no trend observed in the energy required to crush the roof between the two plate angle configurations. The S-10 pickups and the Explorers required more energy to crush the roof with the 10x45 degree configuration (25 and 16 percent, respectively), while the Caravan required 12 percent less energy with that plate angle configuration.

When the measured damage patterns were compared for the two sets of load plate angles, it was noted that the 5x25 degree configuration produced more vertical crush, but the 10x45 degree did not consistently produce more lateral crush on either side of the vehicle. When the post-test photographs were compared, the differences in roof damage patterns were not obvious, and would most likely not be noted in a more subjective review of real-world crash investigation cases. Also, compared to the wide range of damage patterns seen in the NASS cases, the differences produced from the two load plate angle configurations were small, so it could be concluded that both configurations produce equally realistic roof damage.

Based on the results of Phase 1, there was no compelling evidence to suggest that a change in the load plate pitch and roll angles would produce more realistic roof damage. Therefore, it was decided that Phase 2 and 3 testing would be conducted using the standard angles of five degrees pitch and 25 degrees roll.

**<u>Phase 2 Summary</u> -** Ten vehicle models were selected for testing in this initial fleet evaluation. Three of these were tested under the selected conditions as part of Phase 1 – a 1997 Dodge Grand Caravan, a 1998 Chevrolet S-10 pickup, and a 2002 Ford Explorer. The other seven vehicles were each tested using only the 5x25 degree configuration. These were a 2002 Ford Mustang, a 2002 Toyota Camry, a 2001 Ford Crown Victoria, a 2002 Honda CR-V, a 2001 Chevrolet Tahoe, a 2002 Dodge Ram 1500 pickup, and a 1999 Ford E-150 Econoline van.

For these ten vehicles, the following procedure was used to evaluate headroom. First, the point representing the top of the head of a normally seated (per FMVSS No. 208) Hybrid-III 50th percentile male dummy was identified and documented. Next, the points on the interior liner and exterior roof directly above the top of the head were identified, marked, and documented. The vertical difference between the roof points and the top of the head was the initial headroom available, to both the interior liner and exterior roof. Three string potentiometers were mounted rigidly to the floor of the vehicle, and were extended and connected at the exterior roof point. Accurate measurements of the three string potentiometer locations and the common attachment point of the roof were made prior to testing. These data, along with the displacement-time histories of the potentiometers recorded during testing, allowed the three-dimensional displacement of the attachment point to be calculated at each moment during the test. The vertical component of this displacement was then subtracted from the initial headroom measurement at each point in time, resulting in a time-history of the headroom remaining. This was done using both the initial headroom to the liner and to the roof.

The force-displacement results from these tests are shown in Figure 11. The force data are presented as a percentage of the unloaded weight of each vehicle, and displacement is that of the load plate, in the direction of plate motion. Vehicle weights, initial headroom measurements, and peak loads are listed in Table 3. All ten vehicles were able to withstand 150 percent of their weight within about 50 millimeters of crush. Nine of the vehicles were able to withstand 200 percent of their weight with no more than 127 millimeters of displacement, six reached the 250 percent level, and only one reached the 300 percent level within the 127-millimeter limit.

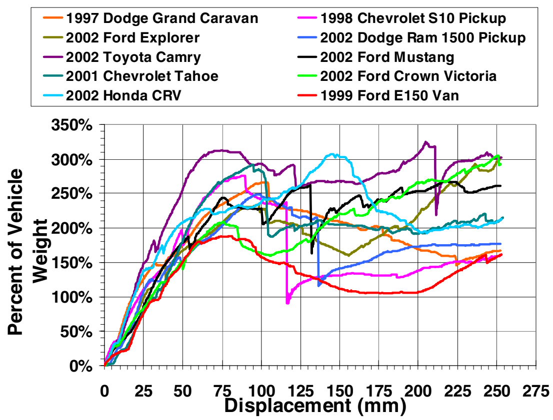


**Figure 11. Phase 2 percent weight vs. displacement.**

The force data (as a percent of unloaded vehicle weight) are shown versus the headroom remaining (to the liner) in Figure 12. All ten vehicles achieved the 150 percent level with most, if not all, of their initial headroom remaining. Nine vehicles reached the 200 percent level, and all nine had 60 millimeters or more of headroom remaining, with eight of these having about 100 millimeters or more left. Only the Ford E-150 van did not reach the 200 percent level before the end of the test (i.e. 254 millimeters of load plate displacement). It should be noted that at the end of the test, the E-150 van still had 56 millimeters of headroom remaining (due to its large amount of initial headroom), and the resistive force was rising again. It is not known how high the force would have reached if the test had been continued until no headroom remained. Eight of the vehicles reached the 250 percent level, and six of these had positive headroom remaining to the liner at that force. Four of the vehicles reached the 300 percent level, but only two of them had positive headroom remaining at that force, and both of these exceeded 100 millimeters.

**Table 3.**
**Phase 2 Test Summary.**

| Vehicle | Vehicle Weight (N) | Initial Headroom (mm) | | Peak Load (N) |
|---|---|---|---|---|
| | | to liner | to roof | |
| Mustang | 13,698 | 90.7 | 98.4 | 36,520 |
| Camry | 13,727 | 116.6 | 149.0 | 44,605 |
| Crown Victoria | 17,525 | 123.6 | 151.8 | 53,461 |
| CR-V | 14,492 | 155.8 | 167.8 | 44,599 |
| Explorer | 18,210 | 121.2 | 149.1 | 55,032 |
| Tahoe | 21,475 | 168.7 | 189.8 | 62,797 |
| S-10 PU | 13,357 | 131.6 | 143.5 | 36,862 |
| Ram 1500 PU | 19,420 | 157.7 | 187.5 | 48,246 |
| Caravan | 16,671 | 138.7 | 169.9 | 44,366 |
| E-150 Van | 22,373 | 191.8 | 253.0 | 42,212 |

The methodology of measuring headroom was also evaluated. Ideally, the motion of multiple attachment points would be recorded, but because of space and data acquisition limitations, only one point could be tracked. The limitation in selecting a single point was that it is not possible to predict prior to the test, which point will be the first to intrude into the occupant's head space.

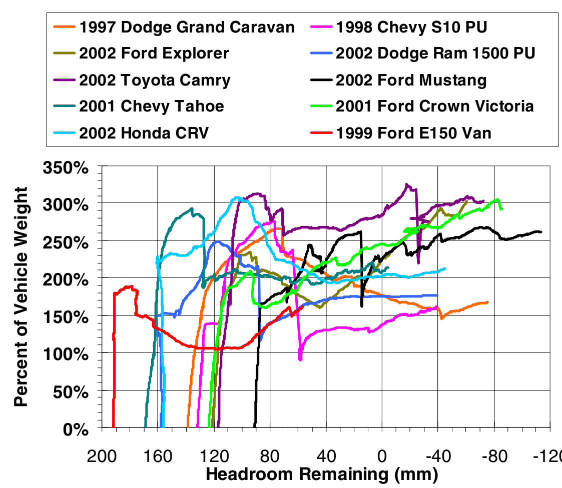


**Figure 12. Phase 2 percent weight vs. headroom to liner.**

Due to the significant amount of lateral displacement of the attachment point during the tests, it was determined that the point above the top of the 50th percentile male head would not likely have been the point of first contact with the head. But, since only the vertical component of the roof attachment point displacement was used to calculate the remaining headroom, for a flat roof, this calculation would be an accurate measure of when the headroom was compromised. For vehicles with more typically curved roofs, this methodology would tend to predict head-roof contact later than it would actually occur, although this is at least partially mitigated due to the curvature of the side of the dummy's head.

Therefore, it was judged that the methodology used in this study for determining the remaining headroom provided a reasonable estimate, particularly since the peak loads generally occurred well before there was no headroom remaining. But, since this was not always the case, a more accurate measure of when the headroom has been compromised was desired.

**<u>Phase 3 Summary</u> -** The Phase 3 tests were conducted using the same procedures as Phase 2, except for the measurement of headroom. Instead of tracking the position of a single point on the roof throughout the test, the point in time at which the interior liner entered the head space of a 50th percentile male occupant was determined. A Hybrid-III dummy was normally seated in the driver's position for the test, and a contact switch was used to document the time of liner-to-head contact. Initial headroom measurements were made in the same manner as for Phase 2. Eleven vehicles were tested in this series. These were a 2003 Ford Focus, a 2003 Chevrolet Cavalier, a 2001 Ford Taurus, a 2003 Chevrolet Impala, a 2003 Subaru Forester, a 2002 Nissan Xterra, a 2004 Honda Element (crushed to 222 millimeters, rather than 254 millimeters), a 2003 Ford Expedition, a 2002 Toyota Tacoma, a 2003 Ford-150 pickup, and a 2003 Chevrolet Express van (15-passenger)[13].

The force-displacement results from these tests are shown in Figure 13. Vehicle weights, initial headroom measurements, and peak loads are listed in Table 4. Figure 14 shows the peak resistive forces achieved for both the overall crush events and prior to head-to-liner contact. As can be seen, all 11 vehicles were able to resist at least 200 percent of their weight prior to head-to-liner contact. Eight of them reached the 250 percent level, four reached the 300 percent level, and two exceeded 400 percent. All seven sport utility vehicles, pickups, and van (LTVs) reached their overall peak force prior to head-to-liner contact. All four passenger cars, on the other hand, reached their overall peak force after head-to-liner contact occurred.

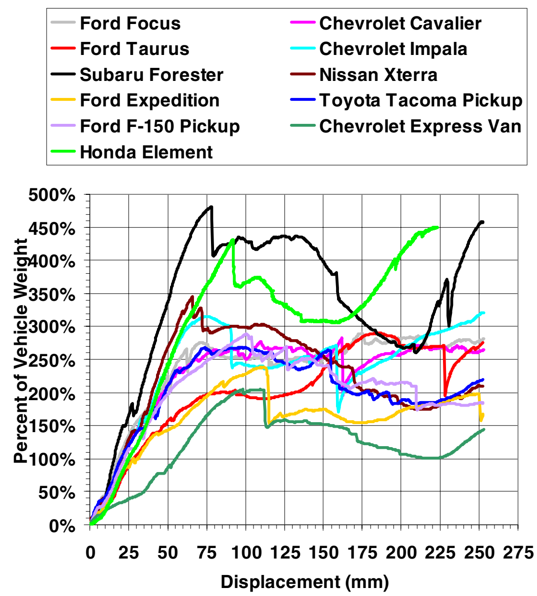


**Figure 13. Phase 3 percent weight vs. displacement.**

**Table 4.**
**Phase 3 Test Summary.**

| Vehicle | Vehicle Weight (N) | Initial Headroom (mm) | | Overall Peak Load | Peak Load Prior to Head-Liner Contact |
|---|---|---|---|---|---|
| | | to liner | to roof | N | N |
| Focus | 11,347 | 120.6 | 145.2 | 32,891 | 31,399 |
| Cavalier | 13,215 | 87.8 | 125.1 | 37,352 | 34,946 |
| Taurus | 14,816 | 133.0 | 153.2 | 43,000 | 30,109 |
| Impala | 15,074 | 125.9 | 152.2 | 48,443 | 47,591 |
| Forester | 13,744 | 145.9 | 183.4 | 66,136 | 66,136 |
| Xterra | 15,421 | 109.5 | 131.3 | 53,359 | 53,359 |
| Element | 15,456 | 228.6 | ND | 69,392 | 69,392 |
| Expedition | 24,090 | 144.0 | 187.3 | 57,369 | 57,369 |
| Tacoma | 13,767 | 100.5 | 112.4 | 37,039 | 37,039 |
| F-150 PU | 18,059 | 162.6 | 176.5 | 52,136 | 52,136 |
| Express Van | 28,169 | 151.0 | 192.7 | 57,661 | 57,661 |

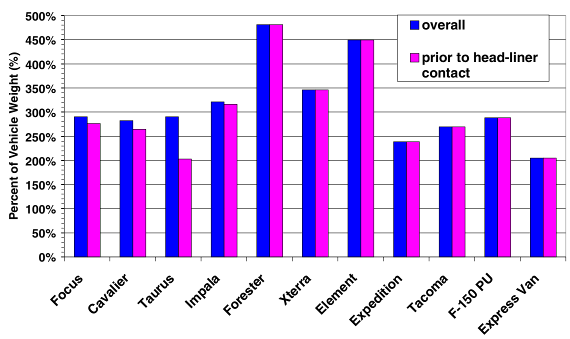


**Figure 14. Phase 3 peak force measurements.**

## IMPROVED RESTRAINTS IN ROLLOVERS

Improvements to FMVSS No. 216 alone may not eliminate occupant contact with the roof in rollover accidents. In a conventional 3-point safety belt, inherent slack and stretch in the restraint system might contribute to occupant contact with an undeformed roof during a rollover crash. It is reasoned that improved performance of occupant restraints could prevent more occupant-to-roof injuries in rollovers.

In the mid-1990s, NHTSA initiated a research program to explore the effectiveness of various restraints in rollovers. A rollover restraint tester (RRT) was developed to simulate rollover conditions. It provided a controlled roll rate for a seated occupant and was followed by a simulated roof-to-ground impact. Occupant excursions toward the 'roof' were measured for common 3-point belt and other advanced restraints systems.

The advanced systems included a 3-point belt with a pretensioner and also a shoulder inflatable belt. Limited testing indicated that the inflatable belt performed the best, reducing occupant excursion by up to 75 percent when compared to the standard 3-point belt with a 50$^{th}$ percentile male [14]. Due to agency priorities being redirected to address emerging frontal air bag deployment issues in the late 1990s, this program was suspended.

With interest in FMVSS No. 216 improvements and previous work highlighting the potential effectiveness of advanced restraints, this revived research program will provide an opportunity to evaluate currently and potentially available state-of-the-art countermeasures to improve occupant protection during a rollover.

**<u>Objectives</u> -** The main objective of the current research is to evaluate the effectiveness of current and advanced restraints in rollover crashes.

Currently, a number of automotive suppliers are working to improve restraint systems for rollover accidents. These existing and new restraint systems include, but are not limited to, integrated seats, pretensioners, inflating seat belts, curtains and pelvic style air bags. Many strategies to provide effective rollover restraint utilize inflatable devices in various combinations. These various options offer many challenges, underscoring the need to develop a research-oriented performance knowledge base.

**<u>Test Device</u>** - Another device, similar to the original RRT, has been developed for continuation of this program. The rollover simulated is one in which the vehicle becomes airborne at the initiation of the roll and then impacts the roof structure after rotating approximately 180 degrees.

Figure 15 is a schematic of the new rollover restraint test device. The device has four (4) main features consisting of

1) A support framework,
2) A counter-balanced test platform with rotating axle,
3) A free weight drop tower assembly, and
4) A shock tower.

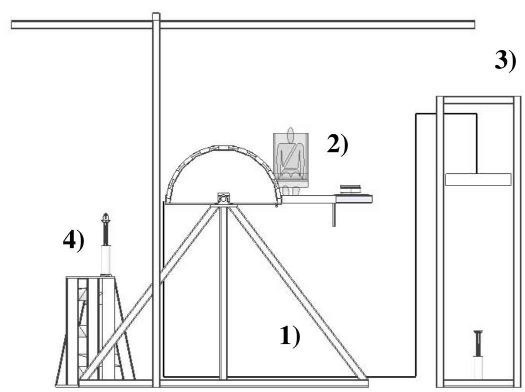


**Figure 15. Rollover restraint tester.**

The test platform, with vehicle seat, dummy and restraint device(s) attached, is mounted to the supporting framework. The free weight drop tower provides energy to rotate the test platform at a desired roll rate. Roll rate can be adjusted by changing the weight of the drop tower mass. To simulate the roof impact, the rotating platform impacts an adjustable shock-absorbing tower after approximately 180 degrees of rotation. Adjusting the shocks can allow testing of various impact pulses, simulating different 'stiffness' values of roof structures.

**<u>Proposed Testing</u> -** A preliminary set of tests will be used to verify the repeatability of the test device. Baseline tests will be conducted using a fleet representative front bucket seat with a standard, non-integrated lap and shoulder belt restraint system. The effect of varying D-ring position, a common mechanism for improving shoulder belt fit, will be evaluated in this initial 'verification' test format.

Each test will consist of a static and dynamic procedure. The static procedure consists of pre-test dummy measurements in both the upright and the inverted impact positions. This procedure will be used to analyze the innate belt slack and dummy excursion exclusive to each restraint system.

The dynamic test procedure will utilize the free-falling drop tower mass to provide a prescribed test platform roll rate. The selected dummy and restraint system will experience the desired kinematics through approximately 180 degrees of rotation until the impact occurs. The marked event will occur when the test platform first makes contact with the shock tower. Approximately two seconds of pre-event and one second of post event data will be collected during the dynamic test. Pre and post-test photographs and test video will be used to evaluate dummy excursion and restraint performance.

A specific test matrix will be designed to optimally evaluate various restraint systems that have the potential to mitigate excursion and/or injury in rollover accidents.

Much of the success and benefit from this research will be driven by cooperative efforts with first-stage suppliers and OEMs. This research could lead to the development of a test procedure(s), a test device(s), and more importantly, improved restraint systems for mitigating injuries during rollover events.

## SUMMARY

NHTSA's crashworthiness rollover research efforts have been following through on the initiatives outlined in the Rollover IPT report. Considerable research has been completed in the ejection mitigation and roof crush area. There is considerable future research to be done to evaluate the effectiveness of restraint systems in rollover crashes and to develop test method(s) for evaluating rollover sensors.

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